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**Observational Studies of the Clearing Phase  
in Proto-Planetary Disk Systems**

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Annual Report for NASW - 4756:  
Observational Studies of the Clearing Phase in Proto-Planetary Disk Systems

for the period March 19, 1993 - March 18, 1994.

Work on NASW-4756 during the first year is summarized below. Since we have been reporting the progress on a quarterly basis, results from the first 9 months are summarized briefly. Work during the last quarter, which has not previously been reported, is discussed.

- Identification of New Proto-Planetary Disk Systems from IUE and IR data: We have identified accreting gas in the line of sight to HD 176386 (B9), HD 35929 (A7e), HD 95881 (A2e), HD 100546 (B8e), HD 50138 (B8e), and HD 45677 (B2e) from IUE data. The more northerly and better studied of these stars exhibit large amplitude light and color variations as well as a trend of increasing polarization with decreasing light, similar to that noted for UX Ori (Grinin et al. 1991).
- Identification of Edge-On PPDS Systems: Coupling the high dispersion observations with the disk model of Grinin et al. (1991) has enabled us to determine that a) the better studied Herbig Ae/Be stars with large amplitude light variations show optical signatures of accreting gas. Velocities range up to a few hundred km/s, suggesting that we are detecting material in free-fall. As a result, we can identify Orion population variable stars with light amplitudes of more than 1 magnitude as being proto-planetary disk systems which we view through the disk. In the course of the last year our sample of such systems has gone from 2 (HD 176386 and HR 5999) in addition to 51 Oph and  $\beta$  Pic itself to more than 30 that are sufficiently bright that we can obtain UV data with IUE. We find that the association of accreting gas with large amplitude light variations also holds for Classical T Tauri stars, thus expanding our sample from B2 to K2 in spectral type, and covering a range in stellar mass from 6 solar masses down to 1 solar mass or less. Our grid of stars is now sufficiently large that we can begin comparative studies of the mass accretion rate, circumstellar extinction, and grain chemistry.
- HD 45677 (B2e): A poster paper entitled "The Growth of Solids and Radiation Shielding In the Young Stellar Disk of HD 45677" by Brown, Buss, Grady, Bjorkman, and Schulte-Ladbeck was presented at the January 1994 AA S meeting. Using HUT data for HD 45677 and HD 200775, we find an upper limit of  $N(\text{H}_2) < 10^{19} \text{ cm}^{-2}$  and measure  $N(\text{H I}) = 2.5 \times 10^{21} \text{ cm}^{-2}$ . The  $\text{H}_2$  upper limit is consistent with the lack of detection of CO and OH molecules in IUE spectra. We find  $R=6.2$  for the HUT observation, indicating that the grains are significantly larger than in molecular clouds ( $R < 5.6$ ). Moreover the inferred fraction ( $f = 7.9 \times 10^{-3}$ ) of H-atoms in molecules compared to total H-atoms is much less in the HD 45677 disk than in molecular clouds ( $f \approx 0.5$ ). We find disk

FUV absorption in excess of the level predicted for graphite-silicate grains (Cardelli et al. 1989), and with the same shape as that of hydrocarbon molecules, such as PAHs, indicating that there are large molecules in the disk. These hydrocarbons can shield the outer parts of the protoplanetary disk from FUV radiation, though not sufficiently to prevent photo-dissociation of  $H_2$ . Thus both the dust and gas in the disk have evolved since formation of the system out of the Galactic medium. The lack of diatomic molecules in the disk suggests that if rocky planetary cores form in the HD 45677 disk they will be unable to accrete a sufficiently larger volatile-rich envelope to produce planetary bodies similar to Jupiter. A paper summarizing these results has been submitted to the ApJ (Letters).

- UX Orionis (A2e): A paper entitled "The  $\beta$  Pictoris Phenomenon in Young Stars: 2. UV Observations of the Herbig Ae Star UX Orionis" by Grady, Pérez, Thé, Grinin, de Winter, Johnson, Yusef-Zadeh, Talavera, Blondel, Tjin A Dje, and Calvet has been submitted to Astronomy and Astrophysics. By intercomparing IUE low dispersion spectra obtained at optical maximum and minimum light we find a bipolar emission nebula becomes detectable when the star light is heavily attenuated by dense dust clouds in the line of sight. Using the pair method and the optical maximum spectrum as the comparison spectrum, we find that the circumstellar extinction can be characterized in the UV by  $R=7-8$ , consistent with the optical photometry. At optical maximum, however,  $R=5.0$ , indicating that the dense dust clouds are not only more opaque than the average disk, but are composed of significantly larger particles. At optical minimum we detect a strong dust-scattered light component, in agreement with the model of Grinin et al. (1994). Collectively our data strengthen the recent argument by Grinin et al. (1994) that the dense dust clouds represent the comae of star-grazing comets.
- Preliminary Evolutionary Studies: A poster paper on the results of the IUE minimum light studies of a number of Herbig Ae/Be stars viewed with the same orientation as for  $\beta$  Pic was presented at the AAS meeting held in Crystal City, VA in mid-January 1994. We find that the luminosity of the bipolar emission line regions scales with the IR excess at 12 microns. UV excesses at minimum light, when the star is heavily obscured by dense dust clouds in the circumstellar disk, also scale with the IR excess. Perusal of optical line profiles in the literature also suggests that the line-of-sight accretion rate is a function of the IR excess. In collaboration with Sitko (U. Cincinnati) we have begun a survey of the edge-on systems with IRAS LRS data. For the isolated systems, where source confusion is not an issue, we find a trend of decreasing prominence of the 10 micron silicate emission feature relative to the 18 micron feature as the IR excess decreases. As noted by Pollack et al. (1994) this is consistent with a trend of increasing near-stellar silicate grain size with decreasing IR excess. Collectively these data suggest that we should be able to quantitatively explore the clearing of the near-stellar regions of PMS stars. Preparation of a paper to be submitted to the *Astrophysical Journal* is pending acquisition of IUE observations for a few more systems with small IR excesses.

- **IUE Observations:** Much of the effort during the last quarter has been to acquire additional UV observations of a number of Herbig Ae/Be stars during the IUE 17th episode. A total of 7US and 1 ESA shifts were scheduled from mid-January through late March 1994. We acquired the HD 35929 data, optical minimum observations of the classical T Tauri star RW Aur, and additional observations of HD 50183, HD 45677, BF Ori, and RY Tau. The UV observations were coordinated with optical spectra from CTIO, ESO, Ritter, and Lick. Optical and UV photometry have been obtained from ESO, Corralitos Observatory, and Mt Lemmon (IR). The February observations were coordinated with 8-13 micron spectrometry lead by Diane Wooden (NASA/Ames).
- **HD 35929:** After being alerted to the interesting IR spectral energy distribution of this comparatively bright ( $V=8.2$ ) and under-studied Herbig Ae star, we obtained a set of IUE low and high dispersion spectra over the interval January-March 1994. The IUE data show accreting gas, collisionally ionized material similar to that seen in both  $\beta$  Pic and HR 5999, and provide indications of a bipolar emission line region similar to that seen at optical minimum toward a number of the edge-on systems. This star appears to have a disk which is intermediate in character between that of the bona-fide PMS Herbig Ae stars and main sequence systems like  $\beta$  Pic.
- **RW Aur:** IUE observations of this classical T Tauri Star at  $V=11.3$ , the faintest that it has been observed at with the IUE were made in January and early February 1994. We find a faint, featureless continuum in the 2400-3000 Å range, similar to that seen at optical minimum for other edge-on disk systems. No Fe II emission was detected. Prominent Mg II emission was present. A high dispersion spectrum revealed a complex emission profile which does not resemble the type III P Cygni profile seen at optical maximum light. Instead the profile closely resembles the [O I]6300 emission presented by Hamann (1994) and interpreted as emission arising from a disk wind and bipolar jets. The Mg II data are consistent with the lack of detection of high velocity Ly  $\alpha$  emission in the January 23 observation, and suggest that the Ly  $\alpha$  emission routinely seen in low dispersion, independent of the degree of obscuration of the star, is preferentially produced in the bipolar jet and is unaffected by circumstellar extinction. A paper will be completed once the ground-based observers have an opportunity to analyze their data.

#### **Publications To Date:**

##### **A. Refereed:**

1. Grady, C.A., Bjorkman, K.S., Shepherd, D., Schulte-Ladbeck, R.E., Pérez, M.R., de Winter, D., and Thé, P.S. 1993, "Detection of Accreting Gas Toward HD 45677: A Newly Recognized, Herbig Be Proto-Planetary System", *ApJ (Letters)*, 415, L39.

2. Brown, T., Buss, R., Jr., Grady, C., Bjorkman, K., Schulte-Ladbeck, R., 1994, "The Growth of Solids and Radiation Shielding in the Young Stellar Disk of HD 45677", *ApJ (Letters)* (submitted).
3. Grady, C.A., Pérez, M.R., Thé, P.S., Grinin, V.P., de Winter, D., Johnson, S.D., Yusef-Zadeh, F., Talavera, A., Blondel, P.F.C., Tjin A Dje, H.R.E., Calvet, N. 1994, "The  $\beta$  Pictoris Phenomena Among Young Stars. II. Ultraviolet Observations of the Herbig Ae Star UX Orionis", *A&A* (submitted).
4. Waters, L.B.F.M., van den Ancker, M., Baas, F., van der Blik, N.S., Bontekoe, R., Grady, C.A., Kester, D.J.M., Oudmaijer, R.D., Sandell, G., Thé, P.S., Vega, R., and van Winckel, H., 1994, "Circumstellar Gas and Dust in 68 Ophiuchi (A0 IVe)", *A&A* (submitted).

#### B. Conference Proceedings:

1. Grady, C.A., Pérez, M.R., de Winter, D., and Thé, P.S., Yusef-Zadeh, F., and Johnson, S.D. 1993, "Detection of a Bipolar Flow Associated With UX Ori: An Intermediate Mass Pre-Main Sequence Star", to appear in *"Frontiers of Space and Ground-based Astronomy: The Astrophysics of the 21st Century"*, editors, M. Longair, W. Wamsteker, and Y. Kondo (Dordrecht: Kluwer) (in press).
2. Grady, C.A., Pérez, M.R., Thé, P.S., de Winter, D., Yusef-Zadeh, F., Johnson, S.D., and Grinin, V.P. 1993, "Low Dispersion UV Spectral Variability in 3 Herbig Ae Stars Viewed Through Their Circumstellar Proto-Planetary Disks", *BAAS* **25**, 905.
3. Grady, C.A., Pérez, M.R., and Thé, P.S. 1993, "HD 45677 and HD 50138: Identification of 2 B[e] Stars as Herbig Be Stars Viewed Through Their Circumstellar Disks", in *The Nature and Evolutionary Status of Herbig Ae/Be Stars*, eds. P.S. Thé, M.R. Pérez, E.J. van den Heuvel, ASP Conference Series, (in press).
4. Grady, C.A., Pérez, M.R., Talavera, A., Thé, P.S., de Winter, D., Grinin, V.P., Calvet, N., 1993, "Iron Emission Lines in the Spectra of Herbig Ae/Be Stars Viewed Through Their Proto-Planetary Disks", *BAAS*, **25**, 1353.
5. Buss, R., Brown, T., Grady, C., Bjorkman, K., Schulte-Ladbeck, R., 1993, "Evolution of Dust toward Planetesimals in the Young Stellar Disk of HD 45677", *BAAS* **25**, 1353.
6. Pérez, M.R., Grady, C.A., Blondel, P.F.C., de Winter, D., Thé, P.S., 1993, "Lyman  $\alpha$  as an Accretion Diagnostics in Young Stellar Objects", *BAAS* **25**, 1352.

Work planned for the Second Year of the 5-Year Study:

1. Continued UV observations of Edge-On Pre-Main Sequence Proto-Planetary Disk Systems: Approximately 1/2 the observing time awarded to our NASA IUE 17th episode program and one ESA shift has yet to be scheduled. We plan a series of observations coordinated with ESO CAT and photometric observations in August-September 1994. We will also be applied for additional observing time during the 18th episode to obtain data on additional systems in the Orion star formation region, and to support Astro-2 observations of the brighter proto-planetary disk systems. The proposal for ESA time (A. Talavera is PI) has already been submitted. These observations are part of a observing consortium study in collaboration with Mike Sitko (U. Cincinnati), Diane Wooden (NASA/Ames), Pik-Sin Thé (Amsterdam), and Vladimir Grinin (Crimean Astrophysical Observatory). Where feasible, optical photometry, spectroscopy, polarimetry, and spectropolarimetry will be obtained. IR photometry and 8-13 micron spectrometry will be obtained for selected observation dates.

2. Circumstellar Extinction/Scattered Light Studies: Once the data are available, we plan to expand our circumstellar extinction/scattered light studies for UX Ori to as many of the other edge-on systems as feasible. We have access to single-Mie scattering models for the average disk calculated by Vladimir Grinin. Since our preliminary explorations of these models suggest that the grain size distribution which successfully fits the optical data greatly overestimates the number of small grains contributing to the UV scattered light component, we plan to work on a series of simple models which will allow us to explore the disk grain properties. These data will be used to analyze the IUE data, archival HUT and WUPPE data for HD 45677, and observations of similar systems to be made with HUT and WUPPE on Astro-2.

3. Bipolar Emission Line Studies: In collaboration with Mario Pérez (ARC), we will continue to expand the bipolar emission line studies at optical minimum light to additional objects. We will also participate in a proposed study of Ly $\alpha$  emission in these systems to separate the disk component from the more extended jet/bipolar flow. Extension of our sample to T Tauri stars will enable us to explore the effects of stellar mass and the presence of magnetic fields on the bipolar emission line regions. We anticipate that this program will be a precursor to an HST Cycle 5 proposal.

4. The Evolutionary Study for mid-late Ae stars: We plan to publish one or more papers on the evolution of the disk material, with a focus on stars similar in mass to  $\beta$  Pic.



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16. Abstract A summary of work completed during the first year of a 5 year program to observationally study the clearing phase of proto-planetary disks is presented. Analysis of archival and current IUE data, together with supporting optical observations has resulted in the identification of 6 new proto-planetary disk systems associated with Herbig Ae/Be stars, the evolutionary precursors of the $\beta$ Pictoris system. These systems exhibit large amplitude light and optical color variations which enable us to identify additional systems which are viewed through their circumstellar disks, including a number of classical T Tauri stars. On-going IUE observations of Herbig Ae/Be and T Tauri stars with this orientation have enabled us to detect bipolar emission plausibly associated with disk winds. Preliminary circumstellar extinction studies have been completed for one star UX Ori. Intercomparison of the available sample of edge-on systems, with stars ranging from 1-6 solar masses, suggests that the signatures of accreting gas, disk winds and bipolar flows, and the prominence of a dust-scattered light contribution to the integrated light of the system decreases with decreasing IR excess.			
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